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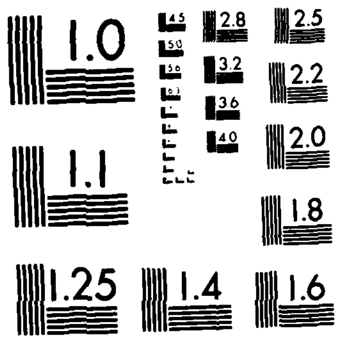

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of the

Selected Research Program of the Office of Naval Research

at the

Center for Wave Phenomena, Colorado School of Mines

Principal Investigators

Norman Bleistein, Jack K. Cohen,

Frank G. Hagin, John A. DeSanto

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PROGRESS REPORT, OCTOBER 1, 1984

CENTER FOR WAVE PHENOMENA

This is a progress report on the current status of the research program of the Center for Wave Phenomena at the Colorado School of Mines. There are presently five faculty members and seven graduate students supported by this program; three additional students are working on research projects with Center faculty. The Center derives its research support from four sources: The Selected Research Opportunities Program of the Office of Naval Research (SRO), The Consortium Project on Inverse Methods for Complex Structures (CP) supported by ten energy companies — Amoco, Conoco, Golden Geophysical, Marathon, Mobil, Phillips, Sun, Texaco, Union and Western Geophysical — the Ocean Acoustics Program of the Office of Naval Research (OA) and the Colorado School of Mines (through reduced teaching loads over and above the reduction supported by research contracts).

The People

The five faculty members are Norman Bleistein, Jack K. Cohen, John A. DeSanto, Frank G. Hagin and Robert D. Mager. The Selected Research Opportunities project partially supports Bleistein, Cohen, DeSanto and Hagin. The Ocean Acoustics project partially supports DeSanto. The Consortium project partially supports Bleistein, Cohen, Hagin and Mager. The School of Mines partially supports all five members.

The graduate students and their support are as follows: Linda Boden (OA), Paul Docherty (SRO), Peter Kaczkowski (SRO), Kingsley Smith (CP), Brian Sumner (CP), Michael Sullivan (CP), Shelby Worley (SRO).

Related Activities

We would also like to report on some other activities which have relevance to our research and educational activities at 'Mines.

In the Fall '84 semester the CWP faculty members are teaching the following courses: Bleistein, Applied Complex Variables (Mathematics Department); Cohen, Seismic Inverse Methods (Geophysics Department); DeSanto, Ocean Acoustics (Geophysics Department); Hagin, Applied Functional Analysis (Mathematics Department); Mager, Seismic Data Processing (Geophysics Department).

The Colorado School of Mines will soon be receiving a gift of two computers, a model 6050 and model 9750 from Gould, Inc. These computers are to be devoted to graduate education and research. Two CWP people played important roles in negotiating this gift. Robert Mager made the initial contact with Gould and Frank Hagin chaired the Research Computer Committee and was involved in direct negotiations with Gould management to establish this donation. The approximate value of this gift is $700,000.

The school has also received a gift of 250 hours valued at $500,000 on a Denelcor super computer. Jack Cohen has been discussing a demonstration project with the School's technical liaison at Denelcor.

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Norman Bleistein made a presentation at the London meeting of the European Association of Exploration Geophysicists in June. He also presented an invited Plenary Lecture at a symposium on nonlinear problems in differential equations at the University of Dundee, Scotland. In May, he taught a short course at the Naval Underwater Systems Center in New London, CT, on multi-valued functions with applications to the analysis of Fourier integrals. In December, he will teach another short course in New London based on his new book, Mathematical Methods for Wave Phenomena, which was published in July. He has also accepted an invitation to write an article on wave propagation for an Encyclopedia of Science to be published by Academic Press.

John DeSanto visited Woods Hole Oceanographic Institute as the H. Burr Steinbach Visiting Scholar in July. He and Gary Brown of Applied Science Associates, Inc., in North Carolina, had a joint invited paper at the International URSI Symposium in Florence, Italy in August. They are jointly writing a review article on Scattering From Rough Surfaces for the PROGRESS IN OPTICS series of books, edited by Emil Wolf, University of Rochester. DeSanto also presented an invited paper at the Yale Conference of Computational Ocean Acoustics. The Encyclopedia of Physics (Edited by R. Besancon) is also scheduled to be published this year, including a chapter by DeSanto on Ocean Acoustics.

We will have two longterm visitors during the present academic year. George Frisk, Woods Hole Oceanographic Institute, will be here for the month of February and David Stickler, Courant Institute of Mathematical Sciences, will be here in March and April. These visits will be supported by the SRO program.

In addition, A. J. Berkhout, Delft University, and some of his students will visit here during the week of November 26.

Research Background

The objective of our research is to produce inverse methods to describe the structure of the earth and the oceans for seismic exploration, seabed mapping and ocean modeling. All of the problems we treat are nonlinear. Our approach is to derive approximate solutions of linearized problems which estimate the earth or ocean parameters as perturbations from a known background structure. Thus, the closer the background structure is to the true medium, the smaller the perturbations and the more accurate the inversion methods. This is the reason for our desire for inversion techniques for progressively more complex background structure.

There is a fundamental idea which pervades our research, namely, asymptotic inversion of data for structure and parameter estimation. Asymptotics arise naturally in the problems we model since most length scales of the problem are many wavelengths long.

We model the experiment of interest by deriving an integral representation for the observed wavefield produced by the experiment. Typically, the integrand contains some functional characterization of the perturbation of the medium parameters, multiplied by an amplitude and phase which are functions of the variables of integration (input coordinates) and the coordinates of the observation point. To obtain an asymptotic inversion we multiply by another amplitude and phase (the inversion kernel) which are functions of the observation coordinates and another set of coordinates, the output coordinates. We then integrate over the set of observations and over frequency. The phase of this inversion kernel is always the negative of the phase of the modeling kernel, with the input variables replaced by the output variables. The amplitude is much more difficult to determine. Indeed, much of our inversion research focuses on determining the amplitude of the inversion kernel. The more complex the background structure is, the more difficult it is to determine the amplitude.

In the seismic inverse problem, in the absence of an accurate determination of the amplitude, the method still provides an inversion for structure, alone — similar to a migration algorithm. We refer to such a partial inversion as a **structural inversion**. To distinguish structural inversion from a complete inversion which estimates one or more earth parameters, as well, we refer to the latter as a **seismic inversion**.

The output of a structural inversion algorithm is a reflector map of the interior of the earth. Each reflector is characterized mathematically by its **singular function**. The singular function is a Dirac delta function which peaks at every point on the reflector. We model the earth as a fluid with only the sound speed varying isotropically. Thus, for the present, the only parameter we estimate is reflection strength in a constant density medium[1] from which we obtain an estimate of velocity variation across the reflector. When the array of singular functions of the subsurface is scaled by this reflection strength, we call the output the **reflectivity function** of the subsurface.

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1 In the future, we do anticipate extending our methods to include more parameters.

There are two major differences between the ocean inversion problems and the seismic inversion problems. *The first difference* is that in the ocean problems the propagation of the acoustic field occurs in a direction (range) orthogonal to the major direction of coordinate variability of the sound speed (depth). We can thus take advantage of the natural asymptotics for large range. In geophysical terms, this amounts to very large offset. As in the geophysical problem, this allows us to retain low wave number information in the direction of interest for inversion despite the use of high frequency asymptotics in the orthogonal direction. *The second difference* is that the propagated field is, for the most part, not scattered as in small offset geophysical problems, but rather refracted due to the depth dependence of the sound speed and the resulting interior ocean waveguide it creates.

Research Projects

This past six months has been an extremely productive period in which we are simultaneously solidifying the theoretical basis of our approach to inverse problems and proceeding to develop methods and attendant computer algorithms for inversion in the context of progressively more complex background structure and more realistic models of the basic seismic or ocean experiment. We are also developing our own modeling methods and algorithms as an adjunct to our inversion research.

We shall provide a brief description here of the present status of our research projects without regard to the source of support, since we believe that all projects derive benefit from the synergism of our group activity.

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Jack Cohen, Frank Hagin [1984] and Brian Sumner are working on an inversion for the reflectivity function from zero offset data in the context of a depth dependent background velocity. This work is a continuation of the work by Bleistein and Gray [1984]. In that paper, a structural inversion was derived for this case. A computer program was written to implement the method as a structural inversion. Subsequent research by Cohen and Bleistein showed that the amplitude of that method was not accurate[2] for arbitrary curved reflectors, although the amplitude proposed by Bleistein and Gray was accurate for flat reflectors and reduced to the correct result for the case of a constant background velocity.

In this work, the researchers model the observed data by using the Born approximation with a leading order approximate WKB Green's function for the depth dependent background velocity. Thus, this work is much in the spirit of Cohen and Bleistein [1979] and Clayton and Stolt [1981]. Requiring that the output be an accurate reflectivity function for Kirchhoff-approximate data for an arbitrary curved reflector leads to an equation for the amplitude.

A computer code implementing this method is nearing completion. The code has been tested with a constant background velocity and produces the same benchmark output as the earlier constant background program does. This is not a trivial check. The new program computes travel times and amplitude by integration formulas and must solve for a ray parameter as part of that

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2 "Accurate" for us means that if we use Kirchhoff-approximate data for a single reflector and carry out all integrations asymptotically by the method of stationary phase, then the result is the reflectivity function for the single reflector.

tabulation. In contrast, the older program merely computes those components by straightforward formulas. The new program also properly accounts for spatial aliasing, as did the old one. In addition, the new program incorporates a limit on summation over traces based upon the the premise that some a priori estimate of maximum inclination of reflector is known.

Cohen is also working on the problem of inversion of offset data in a constant background medium. He assumes that all data is taken at constant offset. As suggested above, a structural inversion is already established and has been checked analytically. At this point, it would seem that the complete inversion may require post processing analysis to determine the reflection strength after determining the inclination of the reflector from the structural inversion. We believe that multiple offsets would be used to improve the robustness of the output.

Cohen has also laid out an approach to the case of inversion of constant offset data in a depth dependent background velocity. Again, the choice of phase function of the inversion operator is straightforward and research is necessary to determine the amplitude of the inversion operator.

In much the same spirit, Robert Mager and a graduate student, Jason Kao, are working on the construction of inversion operators based on plane-wave decomposition. this work provides a more consistent approach to the construction of plane-wave migration operators, and extends previous work done in this area to models of variable background velocity.

Progress Report, October 1, 1984

The work is similar to that of Cohen in that a canonical structure for the imaging operator is assumed. This structure again assumes phase functions which are in reverse sign to those predicted by forward Kirchhoff models. The inversion involves integrals over both source and receiver coordinates. The integral over sources provides the plane-wave synthesis, while the integral over receivers provies a backward continuation of the scattered wavefronts. It is possible from this construction to produce the reflectivity function across an interface. However, the determination of velocity requires (as in Cohen's work) a post-processing sequence involving knowledge of reflector tilt.

Our methods produce an accurate estimate of reflection strength at a single reflector for any size jump in velocity across the reflector, even though we started from a Born approximation of the observed wavefield. Thus, the reflection strength need not be small at the reflector of interest. However, the accuracy of the kernel of the integral representation depends upon having only small error in the background velocity above the reflector of interest. These observations have motivated another approach to the seismic inverse problem. In this approach we start from a Kirchhoff-approximate representation of the observed fields. This approach has the advantage that small perturbations of earth parameters at the reflector of interest is no longer an issue.

For constant background, when we start from the Kirchhoff representation of the wave field, the same algorithm has been obtained as with the Born representation. Preliminary analysis indicates that the same will be true for the case of a depth dependent background. Thus, we anticipate in the future starting all of our inversion research from the Kirchhoff representation. This work is being carried out by Jack Cohen and Michael Sullivan with some input from Frank Hagin, Robert Mager and Norman Bleistein.

Brian Sumner [1984] has completed a project of developing a fast Fourier transform (FFT) algorithm which uses powers of 2, 3, 4, 5 and 6, instead of just powers of 2 to improve the speed of the FFT by significantly reducing the number of floating point operations required to calculate an FFT of a prescribed length. Even for a data set whose length is a power of two, the method provides a significant improvement by exploiting powers of four instead. For a data set of a given size, the algorithm does a local search for a nearby optimum length of data field for reduction of CPU operations. This project was carried out almost totally by Sumner with some guidance by Cohen.

Paul Docherty [1984] has been working on a modeling program for ray theoretic in-plane fields in two-and-one-half dimensions ($2^1/_2$D) in a general $c(x,z)$ background velocity — z measured positive downward. By "$2^1/_2$D" we mean three dimensional propagation in a medium with only two dimensional variation of its parameters. By "in-plane" we mean that all sources and receivers are in the (x,z)-plane, with $y = 0$. The type of medium considered here is one in which the velocity is constant in layers whose boundaries are not horizontal.

The method determines the travel time on each ray by iteration, using the travel time on an adjacent ray as a starting guess. For the first ray, the travel time is determined in a horizontally stratified medium, with horizontal layers at the "average" position of the layers of interest. Then the medium is perturbed in the direction of the true medium and the previous solution is used as an initial guess. Typically, one or two such perturbations are all that is needed to vary the structure from horizontally stratified to the true medium. The ray tracing algorithm at the heart of this research is based on work of H. B. Keller and two of his students, J. Fawcett [1983] and D. J. Perozzi (Keller and Perozzi [1983]). Docherty's work is being carried out under the guidance of Norman Bleistein.

The ultimate objective of this research is an inversion with a c(x,z) background. By using an inversion operator of unit amplitude and the correct phase, Docherty has already produced a "quick and dirty" structural inversion in a c(x,z) background.

Motivated by our interest in $2^1/_2$D problems, Bleistein [1984] has recently completed a project in which he derived the asymptotic in-plane Green's function and upward scattered Kirchhoff-approximate wave field from a single reflector in $2^1/_2$D. It is interesting that, even in a c(x,z) medium, one can characterize the out-of-plane geometrical spreading in a fairly simple form. The correct scaling is provided by a ray parameter σ which is neither arc length (for which the magnitude of the derivative of the position vector along the ray is equal to unity), nor travel time (for which that derivative is equal to c(x,z)), but is a parameter for which that derivative has magnitude 1/c(x,z). Thus, we now have a correct analytical expression for the amplitude to be used in $2^1/_2$D in Docherty's program. These results will also prove useful in $2^1/_2$D inversion.

Recently, at the International Conference on Inverse Problems of Acoustic and Elastic Waves, Cornell University, June 4-6, 1984, sponsored by ONR, William Symes, Rice University, suggested a reference which might provide a basis for establishing our asymptotic inversion on a firmer theoretical mathematical basis. Frank Hagin has been investigating that theory. It looks quite promising. If Hagin's investigations prove fruitful, they also hold the promise of providing a systematic method for determination of the amplitude of the inversion algorithm for any background structure and source/receiver arrangement. This research is being carried out with a graduate student, Bruce Zuver. In addition, Kingsley Smith, who has just started under support of our program will work on this project.

Kingsley Smith [1984] is near completion of a master's thesis project in which he implemented the algebraic reconstruction technique applied to vertical seismic profiling due to Mason [1981]. That work was guided by Bleistein. That project is still subject to final revisions and approval by his thesis committee.

Bleistein is also guiding a master's thesis project by Isabelle Ledoux on sign bit processing. In this method, the observed field data is replaced by +1 when it is positive and -1 when it is negative. The data is then processed by our constant background velocity inversion algorithm. The basic idea behind this method is that the plus one's and minus one's preserve the basic phase information of the actual signal, which should provide a structural inversion. On the tests which have been run so far, with a single reflector, this is indeed the case. The error in location is less than one percent, even when 20% noise and 40% noise is added to the signal. For a single reflector, even the reflection strength is only in error by approximately 20%!

The advantage of this method is that it dramatically reduces the amount of data which has to be stored from the seismic experiment in order to produce a structural inversion.

Shelby Worley is near completion of a project on processing data with an algorithm in which the seabed is assumed to be horizontally stratified. Again, this method is based on ray theoretic considerations and accounts for the geometrical spreading in three dimensions for point sources. The method is an extension of the method of Lahlou, Cohen and Bleistein [1983]. In the earlier work, the source and receiver were assumed to be coincident. In this work, the source and receiver are no longer coincident but lie along the same vertical line. This extension was motivated by field data provided to us by George Frisk of Woods Hole Oceanographic Institute. That data fits this extended model.

A whole different class of difficulties arise in DeSanto's work on the ocean inversion problem. Due to the waveguide structure of the experiment being modeled, one cannot assume a constant background velocity because the resulting fields are not sufficiently close to the true fields. An approximate waveguide is necessary for the background structure. The asymptotics is consequently more difficult. The structure of the inversion kernel is different in regions characterized by the local behavior of the background sound speed. Presently he is evaluating the last region of variability of the transformation kernel in the neighborhood of the receiver depth. This kernel relates the sound speed correction to the acoustic data. It arises from a Born-WKB approximation in the travel length coordinate. The inversion procedure is as described above in Cohen's and Mager's work. That is, the inversion operator consists of an integration with a kernel whose phase is just the negative of the phase of the forward problem, with input coordinates replaced by output coordinates. The amplitude in this model is considerably simpler. It consists of only a power of the wavenumber k. The bandwidth necessary to carry out an inversion is also under study. Linda Boden is assisting in this project.

A version of the theory incorporating the upper ocean boundary has been developed.

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